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STATIC AND DYNAMIC PLATE-

BEARING TESTS ON DRY SAND

WITHOUT OVERBURDEN

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U. S. NAVAL CIVIL ENGINEERING LABORATORY

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STATIC AND DYNAMIC PLATE-BEARING TESTS ON DRY
SAND WITHOUT OVERBURDEN

DASA-13.018

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Type C

by

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ABSTRACT

The NCEL atomic blast simulator is intended for testing beams, beam-column
connections, and other relatively narrow structural elements. This report describes
the successful adaptation of the simulator for providing dynamic loads on a bearing
plate on sand and presents some tentative results as a preliminary part of Task
Y-F008-08-03-402, "Fundamental Behavior of Soils Under Time-Dependent Loads."
The dynamic bearing capacity of a 15-inch-diameter bearing plate on dry sand
without overburden was 90 percent higher than the static bearing capacity. Also,
the dynamic bearing modulus was considerably higher than the static; e.g., 226 psi
per inch dynamic versus 137.7 psi per inch static at 0.5 inch plate settlement.

INTRODUCTION

Increased knowledge of the behavior of soils under dynamic loads of the type produced by nuclear weapons is urgently needed by engineers engaged in designing protective structures. In addition to the utility of soil as a radiation shield, the economic and mechanical advantages of utilizing the strength of soil masses by placing protective structures underground are being exploited. The background of information regarding the dynamic strength of soils and the behavior of structures dynamically loaded in soil environments is gradually being enlarged, but the magnitude of loads of interest is steadily increasing. This implies the need for stronger, more expensive structures. More precise information is needed to effect structurally adequate, but economically feasible designs. Therefore, continued research is necessary in the field of soil dynamics.

During the last decade, researchers have done a considerable amount of laboratory experimentation with dynamically loaded soils.[1-5] These experiments have included dynamic triaxial shear testing, studies of pressure-wave transmission through soils in shock tubes, miniature bearing tests, and others. In the field, some opportunities have been afforded to study soil behavior and soil-structure interaction under full-scale conditions during nuclear weapons effects tests. Much valuable information has been developed by some of the laboratory research, but laboratory studies are hampered by the great difficulty of producing soil models which will simulate the behavior of large soil masses under dynamic loads. The modeling difficulty is not present in full-size experiments performed during weapons effects tests in the field, but other problems are there encountered. By no means the least of these is the expense involved in full-scale field testing with nuclear weapons. Other writers[6] have pointed out the problems of instrumentation, nonreproducibility of conditions, uncertainty of load magnitude, and infrequency of testing with which the researcher must contend. The ultimate obstacle to field testing is the ban imposed from time to time on nuclear weapon detonations. The dynamic plate-bearing tests on soil which have been and are being conducted by the Naval Civil Engineering Laboratory in the test pit of the NCEL atomic blast simulator have overcome many of the difficulties mentioned above.

The dynamic bearing capacity experiments at NCEL are conducted under Task Y-F008-08-03-402, "Fundamental Behavior of Soils Under Time-Dependent Loads." Financial support for these tests has been provided by the U. S. Defense

Atomic Support Agency through the Bureau of Yards and Docks, U. S. Navy Department. The experimental work has been performed by the Soils and Pavements Division with the assistance of the Structures Division. The task is part of an overall objective of providing information regarding soil-structure interaction under dynamic loads.

This report describes tests which have been made on 15-inch-diameter and 30-inch-diameter bearing plates on dry sand without overburden. One purpose of these initial studies was to determine the degree of usefulness of the NCEL atomic blast simulator for dynamic soil testing. A second purpose was to make a preliminary study of the dynamic bearing capacity of sand on a footing of substantial size without resorting to nuclear weapon detonations in the field. These first experiments were not expected to yield the desirable ultimate product of specific data for structural designers. Nevertheless, the results of these pilot tests do permit some tentative comparisons of static versus dynamic bearing behavior of sand.

TEST PROGRAM

Background

The design of any engineering laboratory test intended to simulate field conditions is dictated by the prototype field event. Within bounds imposed by available test equipment, and by limitations in knowledge of the true character of the field event, the test is made as realistic as possible. The NCEL plate-bearing test program reported here was intended as a simulation of statically and dynamically loaded spread footings without overburden. It is realized that the behavior of dynamically loaded footings on the surface of the earth is not of primary interest in the design of protective structures. However, as a logical by-product of evaluation of the blast simulator as a soil dynamics testing device, the determination of surface footing behavior should provide guidance for the design of more realistic experiments to be conducted in the future.

Conventional foundation loads are of a long-duration, static nature (exclusive of certain specialized loads imposed by rotating machinery, or loads imposed upon pavement foundations by landing aircraft, surface vehicles, etc.). The bearing capacities of soils under these conventional types of loads have long been determined experimentally. Basically, the determination involves the application of static load increments to a bearing plate resting on the soil. Settlement of the bearing plate under each load increment is observed, and the succeeding load increment is added only after the settlement has essentially stopped. Testing is continued until cessation is dictated by one of the following criteria: (a) the applied load is exceeded by some preselected amount the design load later to be

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placed upon the soil; (b) settlement of the plate becomes excessive for the prototype structure later to be placed upon the soil; or (c) the soil fails to support the applied load. Results of the load-settlement test are plotted in graph form, and from the graph may be determined the failure load and modulus of subgrade reaction values. This modulus is useful in predicting settlement at loads less than failure. Usually, it is spoken of as the "k value" of the soil, and it has the units pounds per square inch per inch of settlement. So common has this test become that reasonably accurate k values for many types of soils at specified densities can be obtained from engineering handbooks. Also, conservative estimates of bearing capacities for various types and conditions of soils have been tabulated. In addition, there are theoretical methods of computing conventional, or static, bearing capacity of continuous footings. Among the most frequently used of these are the Terzaghi formulas.[7] Semiempirical adaptations of these formulas have been developed for various footing configurations. That for a circular footing, such as those of the experiments reported here, is as follows:

$$q_{dr} = 1.3cN_c + \gamma D_f N_q + 0.6 \gamma r N_\gamma$$

in which q_{dr} = bearing capacity (load per unit area)

c = cohesion

γ = soil unit weight

D_f = depth of footing (or depth of overburden)

N_c, N_q, and N_γ are dimensionless bearing-capacity factors whose magnitudes depend upon the angle of internal friction, ϕ, of the soil. Charts are available[7] which disclose magnitudes of the bearing-capacity factors for various angles of friction for soils which are relatively loose and those which are relatively dense. No such widely accepted formulas are available to reveal the bearing capacities of soils loaded dynamically.

Some investigators have made theoretical predictions of soil behavior under various assumed dynamic loads and have written extensive computer programs utilizing those theories. Usually, a highly idealized soil is postulated, and the behavior is analyzed by varying the presumed parameters of the idealized soil. To determine the validity of the predictions, and to refine the theoretical techniques, it is necessary to have some experimental data obtained from tests on real soils

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which have been loaded by real or simulated nuclear blasts. To provide such loads frequently and economically for many research purposes, the atomic blast simulator was developed by NCEL.[6] The blast simulator was used to generate the dynamic loads applied during the plate-bearing experiments reported here.

Test Apparatus and Procedure

Blast Simulator. Reduced to its basic elements, the blast simulator (Figure 1) consists of a test chamber beneath a cylindrical expansion chamber that contains a concentrically placed firing tube. Primacord, an explosive fuse material, is detonated in the firing tube. Gases from the explosion are metered through hundreds of small holes in the firing tube into the expansion chamber. From there, the gases pass through slots in the bottom of the expansion chamber into the test chamber, where they impose pressure upon the item being tested. The test chamber is formed by two flat steel plates (called "skirts") which extend downward from the bottom of the expansion chamber. The plates are parallel, are 8 inches apart, and are welded longitudinally along their upper edges to the bottom of the expansion chamber. An item to be tested is mounted in an appropriate manner between the skirts, where it is subjected to the pressure of the gases of the primacord explosion. The rise-time of the pressure, the duration of the peak pressure, and the character of the pressure decay can be controlled. Beneath the blast simulator is a pit which has reinforced-concrete walls and floor. The pit is 9 feet by 10 feet in plan and 12 feet deep.

Soil Placement   A screened and dried river sand was used as the test soil (see Appendix A, Soil Properties). The sand was placed in the pit from a buttom-dump hopper through a chute similar to a transit-mix concrete chute. It was spread uniformly in 2-foot-thick layers, and each layer was vibrated into place with a Lazan oscillator mounted on an 18-inch-square wooden plate. The oscillator was operated at 15 cycles per second with a force output of ± 60 pounds. It was moved about the surface of each layer in a regular pattern which provided cover of vibration on all areas of the surface of the layer. After vibration of each the density of the layer was measured in three places by the sand-cone method. Following each use of the pit for a bearing test, the sand was loosened by hand shoveling to a depth of 16 to 18 inches and recompacted by operation of the Lazan oscillator upon the surface in the manner previously described.

Approximately 45 tons of sand were required to fill the pit to the 9-foot depth. The time required to remove and recompact this amount of sand for each loading of the bearing plate was considered prohibitive. Therefore, the program of post-test surface loosening and recompaction was adopted. It has been demonstrated previously[8] that sand can be compacted to depths of many feet by vibration.

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It was believed that the program of post-test loosening and vibratory recompaction would return the sand to a density condition near that existing when the sand first was placed in the pit and processed by vibration. Since the available method of in-place density measurement (modified sand cone) was not considered very accurate (see Appendix A), density was not measured after each recompaction. Rather, a systematic routine of soil recompaction was followed rigorously to produce comparable initial conditions for each test loading. The series of plate-bearing tests reported here actually was conducted during three different time periods in the test pit. Each time, sand was placed in the pit and processed as described above. The load-settlement characteristics of the sand were determined on a 15-inch-diameter steel plate under static and dynamic loads. Additional dynamic load tests were made on a 30-inch-diameter plate. Both plates were 1 inch thick.
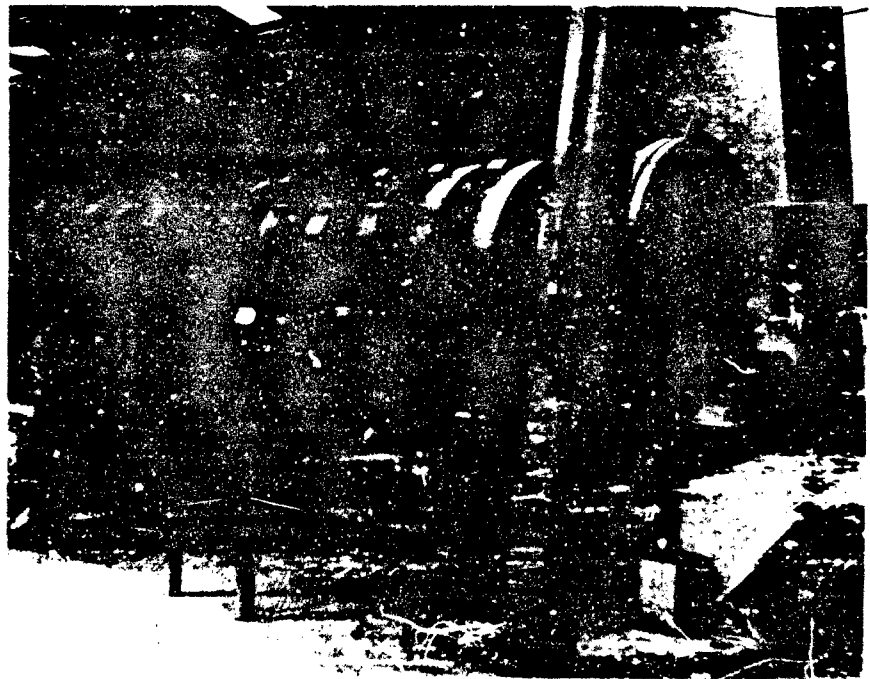

Figure 1. NCEL atomic blast simulator with pit covers in place.

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Dynamic Tests. In essence, the dynamic plate-bearing tests were made by placing sand to a depth of 9 feet in the test pit and dynamically loading a plate on the surface of the sand, utilizing forces generated in the blast simulator. Pressures in the simulator were made to impinge upon a steel beam placed between the skirts. Forces on the beam were transmitted down to the plate on the sand through a vertical steel column welded to the bottom center of the beam. The weight of the beam and column loading device was 915 pounds. Downward movement of the loading system (and hence settlement of the loaded plate) was detected by a linear-motion potentiometer and by a mechanical scriber traveling on a rotating cylinder (see Appendix B, Instrumentation). The mechanical configuration of the loading system limited total settlement to approximately 6 inches. The gross load on the plate was detected by a compression load cell placed between the bottom of the column and the steel bearing plate on the sand. Figure 2 is a schematic view of the test arrangement. Load and settlement information were recorded electronically against the same time base in a recording oscillograph. Figure 3 is a facsimile of one of the test oscillograms.

Static Tests. For conventional bearing tests, the soil preparation and plate placement were the same as for the dynamic tests, except that a hydraulic jack was placed between the plate and the load cell. Static loads were applied by jacking against the load cell, which transmitted the load through the loading column and load beam to react against the frame of the blast simulator. Settlements of the bearing plate were measured by dial-type mechanical strain gages.

RESULTS

Bearing Capacity

The tests reported here produced load-settlement data of static plate-bearing tests on the 15-inch-diameter plate, and load-time and settlement-time histories of dynamic plate-bearing tests on both 15-inch-diameter and 30-inch-diameter plates. Various difficulties with the mountings and other accessories of the potentiometers used for measuring plate settlement made most of the electronic settlement-time records unusable. Figure 3 is a facsimile of one of the few tests made after the difficulty was corrected. However, the electromechanical rotating-cylinder oscillograph (described in Appendix B) functioned very well and produced good records of settlement versus time. Unfortunately, the time bases of the separate electronic load-measuring system and the electromechanical settlement measuring system were not synchronized, and the results can be analyzed only in terms of loading rates, settlement rates, and peak loads versus peak settlements. Table 1 lists these values for the 15-inch and 30-inch plates. Figure 4 is a graph of peak unit load of the 15-inch and 30-inch plates versus rate of plate settlement.

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Correlation lines were determined by the method of least squares. There is a considerable amount of scatter on the graph, but the tendency seems to be toward a faster rate of settlement for a given unit load on the 30-inch plate. This requires future experimental confirmation.

Figure 5 shows three graphs of static load-settlement tests on the 15-inch plate. The average failure load for the three tests was 7.4 tons per square foot. The density of the sand at the times of these tests was approximately 112.1 pounds per cubic foot as measured by the modified sand-cone method (Appendix A). The angle of internal friction (Appendix A) was 43 degrees. Using these values and the bearing-capacity factors from Reference 7, the bearing capacity may be obtained by the Terzaghi bearing-capacity equation for circular footings:

$$q_{dr} = 1.3cN_c + \gamma D_f N_q + 0.6\gamma r N\gamma$$

Since cohesion, c, and overburden, represented by D_f, are both zero, the first two terms drop out, and the equation becomes

$$q_{dr} = 0.6\gamma r N_\gamma$$

$$= 0.6\,(112.1\ \text{lb/ft}^3)\,(7.5\ \text{in.})\,(240)\left(\frac{1\ \text{ft}^3}{1728\ \text{in.}^3}\right)$$

$$= 70\ \text{psi} \approx 5\ \text{tons per square foot}$$

Comparison with the average experimental result indicates the Terzaghi equation gives a somewhat conservative value. As indicated in Appendix A, there is some uncertainty about the magnitude of the unit weight of the sand at the time of the experiment. Trial computations show that even at maximum possible unit weight, the bearing capacity as determined by the Terzaghi method will be less than the average experimental value.
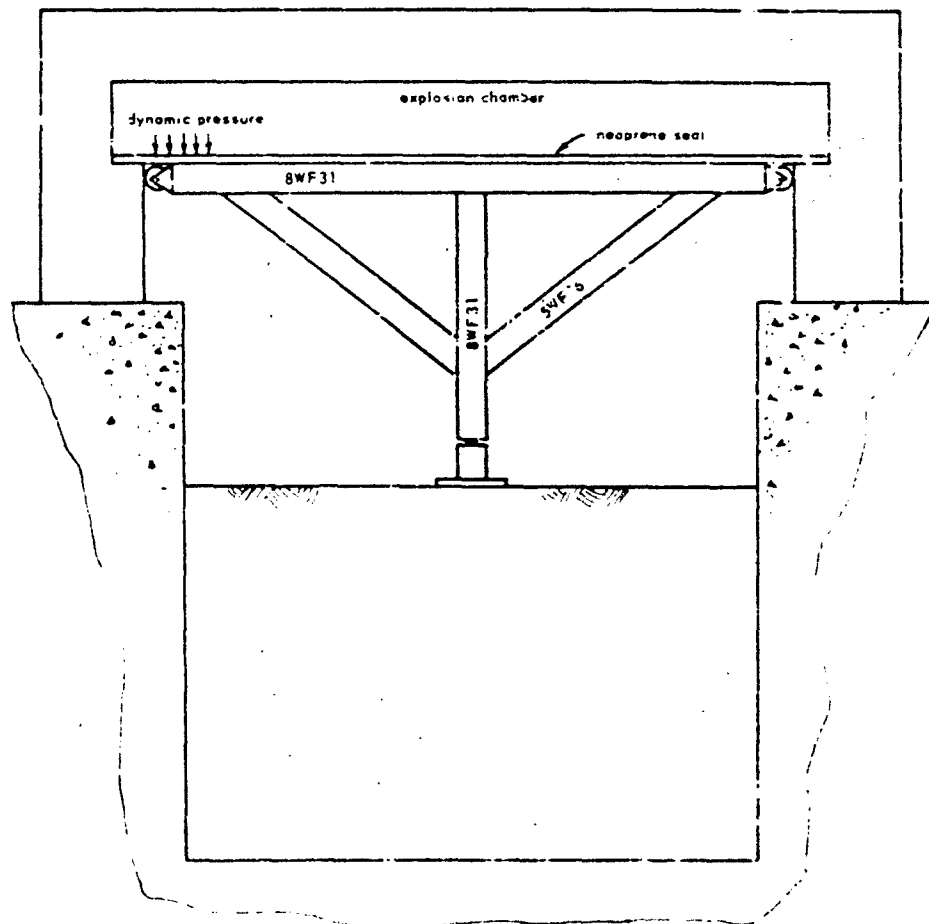
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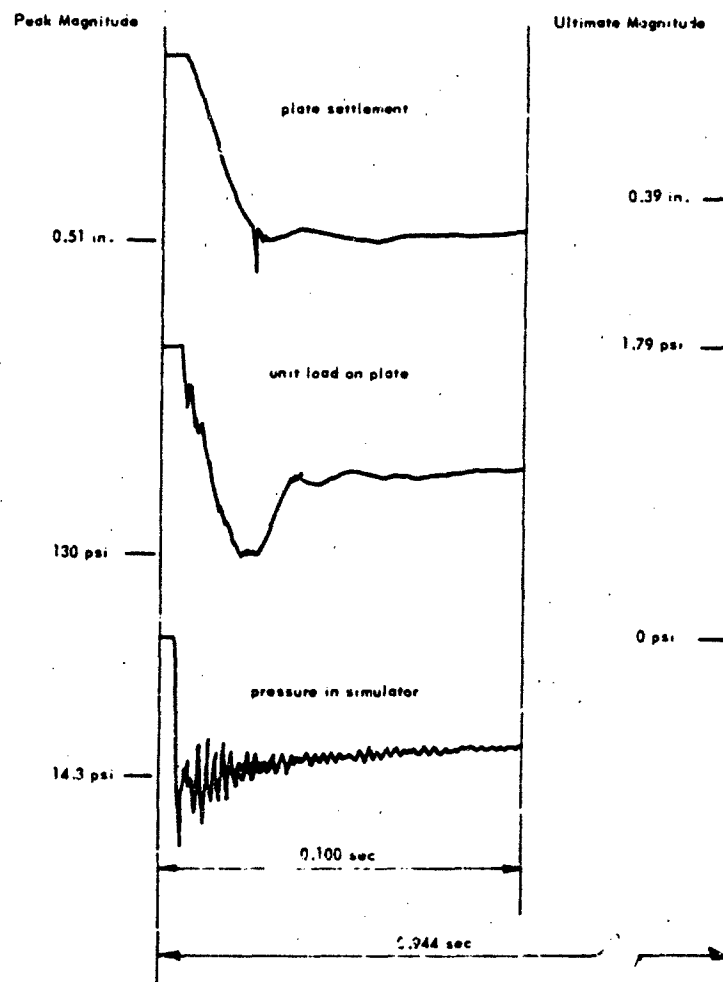Figure 2. Schematic diagram of dynamic bearing test arrangement.

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Figure 3. Facsimile of dynamic bearing test oscillogram (No. 22-...)
on 15-inch-diameter plate.

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Table I. Results of Dynamic Plate-Bearing Tests

| Test Number	Plate Diameter (in.)	Peak Load (psi)	Time to Peak Load (sec)	Loading Rate (psi/sec)	Approx Load Duration (sec)	Plate Settlement Rate (in./sec)	Maximum Plate Settlement (in.)
5-59	15	125.5	0.0086	14,593	—	34.8	0.72
6-59	15	140.1	0.011	12,736	—	59.4	0.98
7-59	15	74.0	0.015	4,933	—	23.5	0.26
8-59	15	172.6	0.0076	22,710	—	86.7	1.30
9-59	15	173.5	0.0097	17,887	—	41.1	1.49
10-59	15	191.2	0.0086	22,233	—	53.4	3.27
8-62	15	87.7	0.017	5,159	0.987	15.5	0.25
9-62	15	163.5	0.012	13,625	1.294	36.8	0.67
10-62	15	158.5	0.023	6,891	1.036	36.1	1.09
12-62	15	198.0	0.022	9,000	1.044	53.5	3.49
22-63	15	130.0	0.017	7,647	0.944	33.8	0.51
26-59	30	38.2	0.0062	6,161	0.998	25.8	0.86
29-59	30	79.6	0.0069	11,536	1.154	49.7	1.68
30-59	30	104.0	0.0062	16,744	1.108	41.3	2.17
31-59	30	161.8	0.0059	27,424	1.130	96.0	2.87
32-59	30	169.4	0.0090	18,822	1.083	59.1	2.60
33-59	30	183.0	0.0135	13,556	1.108	59.2	2.60
38-59	30	213.5	0.0229	9,323	1.173	123.1	2.60
39-59	30	218.8	0.0104	21,038	1.066	69.4	2.47
55-59	30	140.1	0.0129	10,864	0.681	83.4	5.00
56-59	30	144.6	0.0207	6,983	0.478	70.0	3.94
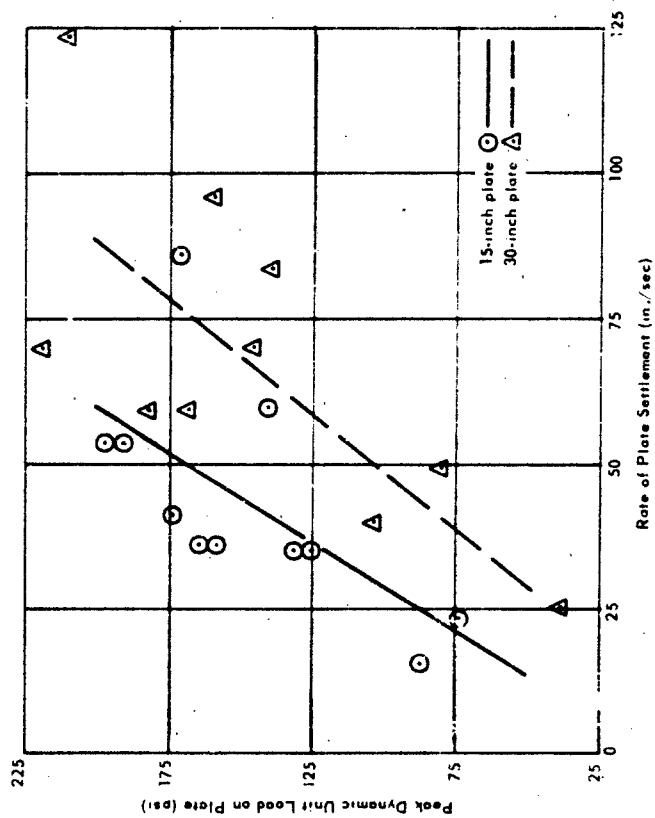
Figure 4 Graph of peak q_i numic unit load versus rate of plate settlement for 15-inch-diameter and 30-inch-diameter plates.
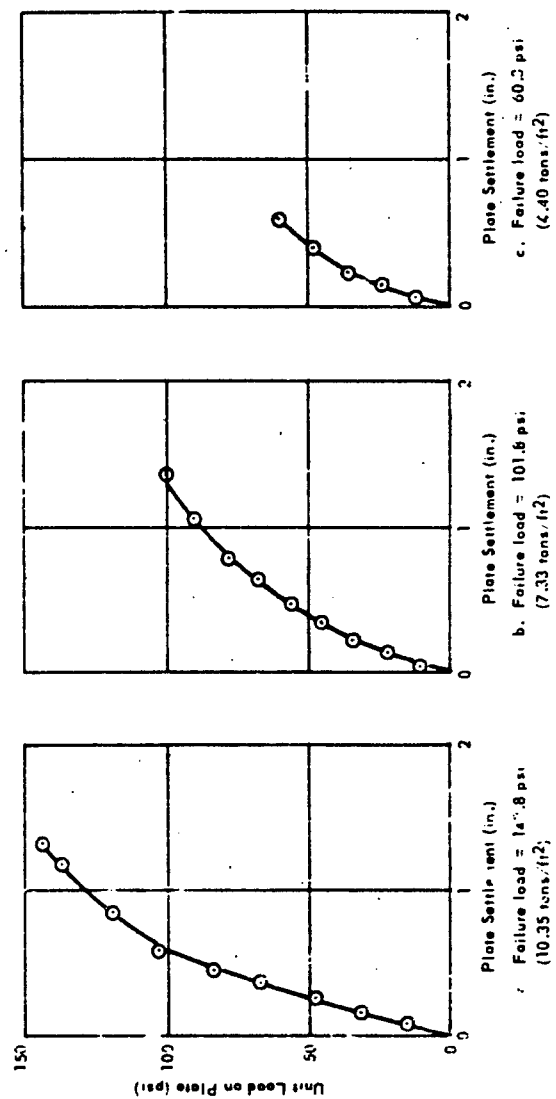
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Figure 5. Static load-bearing tests on 15-inch-diameter plate with no overburden.

a. Failure load = 149.8 psi
(10.35 tons/ft²)

b. Failure load = 101.8 psi
(7.33 tons/ft²)

c. Failure load = 60.2 psi
(4.40 tons/ft²)

Plate Settlement (in.)

Unit Load on Plate (psi)

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Figure 6 is a graph of peak dynamic unit loads on the 15-inch plate versus corresponding peak settlements of the plate. The graph was obtained by plotting the peak load and peak settlement values from each of eleven dynamic tests. The permanent settlement of the plate in most cases amounted to 75 to 90 percent of the peak settlement; but the peak settlement is the critical value in shelter design, and that is the value chosen for Figure 6. The figure shows the peak dynamic unit load carried by the plate to be 196 psi, or 14.1 tons per square foot. This is nearly double the average static experimental value of 7.4 tons per square foot. Figures 7 and 8 are photographs of the 30-inch plate before and after application of a dynamic load. They illustrate the punching type of action which was similar for all dynamic tests in this series.

Bearing Modulus

In addition to the bearing capacity, the bearing modulus or k value also is of interest in shelter design. If means are available to predict load on a footing, the k value will give some idea of the settlement to expect. Though these preliminary experiments were made on circular plates on the soil surface, the relative values of k for static and dynamic loads are significant. Such values of the secant modulus at several amounts of settlement on the 15-inch plate are shown in Table II. As with the bearing capacity, the dynamic secant modulus values are considerably larger than the static values.

Table II. Comparison of Secant Bearing Moduli, k, of
15-Inch-Diameter Plate Loaded Statically
and Dynamically

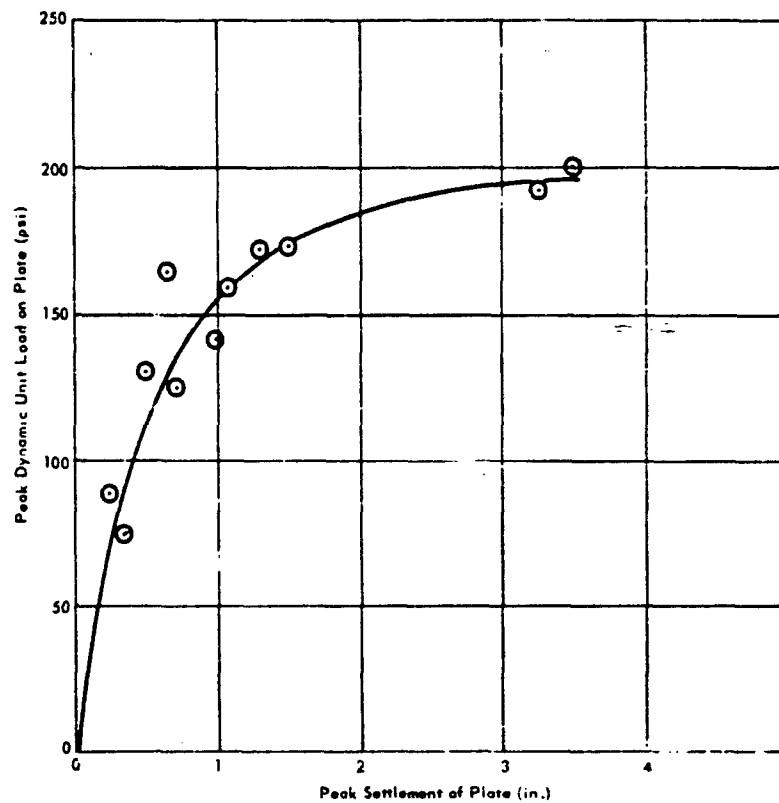| Settlement (in.)	Static k, (psi/in.)	Dynamic k, (psi/in.)
0.25	160.3	296.0
0.50	137.7	226.0
0.75	126.0	184.0
1.00	108.0	156.0

Figure 6. Peak dynamic unit load versus peak settlement of
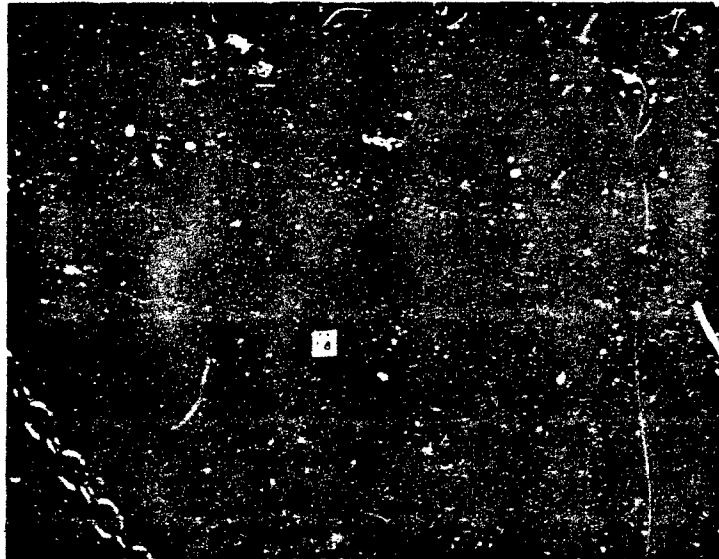15-inch-diameter plate with no overburden.

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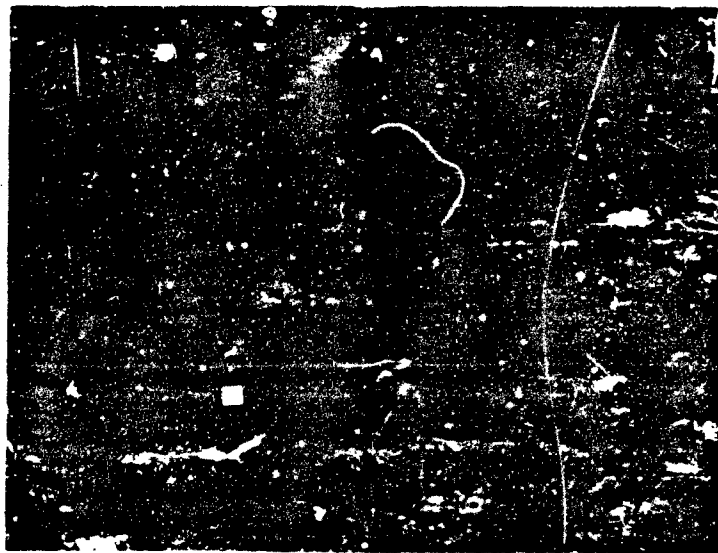Figure 7. 30-inch-diameter plate before application of load.

Figure 8. 30-inch-diameter plate after application of dynamic load.

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Most of the results rep-rted here pertain to the 15-inch plate. Tests on the 30-inch plate were not as fruitful. The relationship between applied dynamic load and plate settlement is not readily apparent from a graph of these data for the larger plate. This may be explained in part by the details of the experimental procedure. Most soil mechanics texts contend that when a footing is loaded the major portion of the soil-stress increase beneath the footing takes place in a zone extending from the soil surface to a depth of 1-1/2 to 2 times the width of the footing. In that zone, an additional effect is an increase of soil density, or unit weight. Such a density increase means that subsequent loadings will produce successively less settlement per unit of applied load on the footing. In conducting experiments to determine the relationship of dynamic load to settlement, the cumulative effects of the loads upon subsequent test settlements are undesirable. Preferably, each test loading should be made upon a soil mass which has had the same load history as all others in the series. Time and cost precluded the provision of a new soil mass for each test in the series reported here. Consequently, the previously described program of surface loosening and recompaction followed each test loading. This reprocessing to a depth of 16 to 18 inches was somewhat effective for the 15-inch plate, since a large percentage of the zone principally affecting the plate behavior was returned to a density reasonably similar for all the tests. However, the zone of significant density increase under a loaded 30-inch plate might extend to a depth of 5 feet. Reprocessing the upper 18 inches would not be sufficient. Such apparently was the case, as may be seen in Figure 9, which shows the dynamic load versus settlement of the 30-inch plate. The number at each data point indicates the chronological order of the tests. Those marked with a subscript "a" were not made during the same test period as the others. That is, the test pit was emptied and refilled between tests marked "8" and "1a." It is nominally true that the pretest load history of point "1a" was similar to that of point "1." The envelope shown by the dashed lines on Figure 9 is an estimate of the range within which a graph of dynamic load-settlement would fall if each test had been made on sand previously not used for a test loading of a 30-inch plate. Being an estimate, the graph shown in Figure 9 is only of minor interest; but if the f- going rea..
is correct, then the envelope shows qualitatively that the dynamic k value decreases with increasing plate size. This may be seen in concept by comparing Figures 6 and 9. Such a relationship between static k value and plate size is well established.[9]

ASSESSMENT OF TESTS

The objective of the work reported here was to obtain some prelimi-ary comparisons of static versus dynamic bearing behavior of sand while evalua: g the blast simulator as a soil-testing device. The number of variables which ultimate!; must be investigated is very large. For this limited trial, they purposely were kept

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to a minimum. Only one type of soil was used, and attempts were made to maintain constant soil density from test to rest. Using dry sand circumvented the necessity of evaluating moisture effects. Two sizes of circular bearing plate were used. However, only the performance of the 15-inch plate has been emphasized. Two types of loading were used. The static loading method was that which has long been employed for building-site investigations. The dynamic loads were simple triangular pulses with sharp rise and exponential decay.

Included among the many factors which must be investigated are (1) the effects of footing size, shape, rigidity, and inertia; (2) soil properties, including the magnitude of the mass involved; and (3) load characteristics, including inertial effects of masses transmitting the loads. After evaluation of these effects, some of which are now being investigated at NCEL, the results will be compared and combined with the work of others, and attempts will be made to formulate theoretical explanations of footing behavior.

The blast simulator facilities at NCEL provide an opportunity to make soils studies in a larger volume of soil than can be utilized at most laboratories. This alleviates, but does not eliminate, undesirable boundary effects. A closer study of those boundary effects is a planned part of future experiments.

In general, the blast simulator worked very well as a loading device for the bearing plates. The magnitude of available dynamic load was ample for the size of footing which reasonably can be tested in the simulator pit. Difficulty was experienced with some instrumentation mountings (Appendix B), but that difficulty has been corrected. A more serious problem was that of controlling the soil conditions. Pouring the soil into the pit through a chute created some grain-size segregation, and undoubtedly contributed to nonuniform density distribution. Some auxiliary effort is needed to perfect handling and placing techniques for the 40 to 50 cubic yards of soil used in these experiments. To this end, some auxiliary tests already have been completed.[10]

With regard to a gain of soil dynamics information, several comments may be made. The numerical values developed in this preliminary study are useful primarily for indicating trends. In part, this is due to the probable errors in data from the 30-inch-diameter plate tests assumed to have been caused by the cumulative increases in density at significant depths beneath the plate. The tests on the 15-inch-diameter plate are more reliable. The limitation in usefulness of both sizes results from the nature of the experiments; i.e., the tests were loads on surface footings, a situation not widely encountered by designers of protective structures. The 15-inch plate tests do serve to show that, under the specific conditions of the tests, the settlement was much less under dynamic load than

under equal static load. Rise-times of the dynamic loads on the plate were on the order of 0.01 second, and load durations were on the order of 1.0 second. The natural period of the sand is estimated to have been approximately 0.065 to 0.075 second, based upon extensive vibratory compaction experiments made upon sand.[8] Even in dry sand, which reaches a state of equilibrium under a statically loaded plate faster than other soils, a dynamic load should not produce as much settlement as an equal static load unless the duration was several hundred times as long as the natural period of the soil. Detonation of nuclear weapons does not produce loads of such duration. Furthermore, the inertia of the soil would tend to reduce settlement under a dynamic load. Therefore, it is reasonable to conclude that comparative values of dynamic versus static load-settlement disclosed by the tests reported here for the 15-inch plate are qualitatively similar to results that would be experienced in the field under nuclear-detonation loads versus static loads.
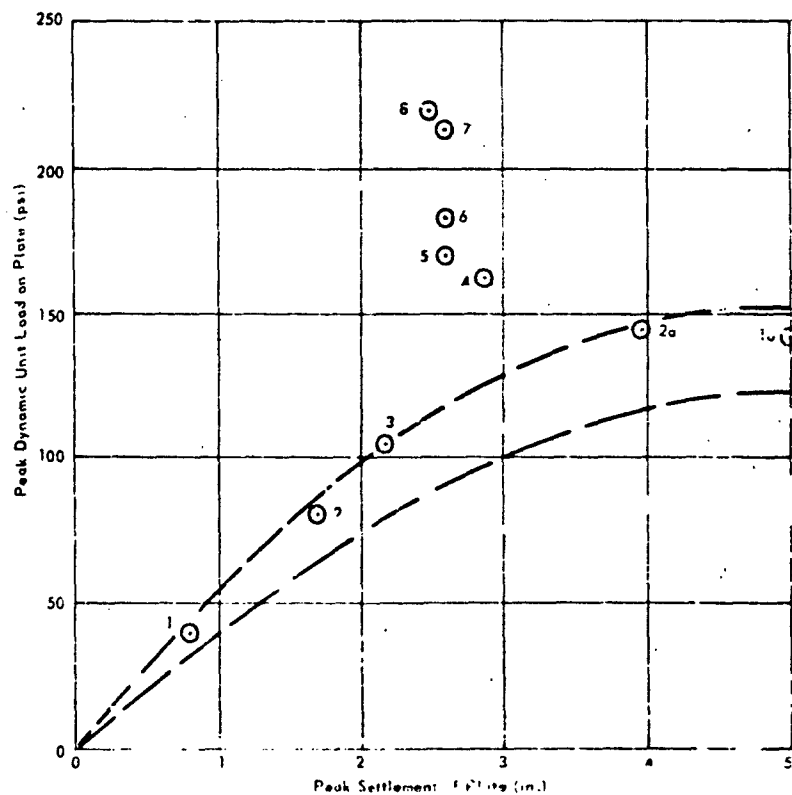

Figure 9. Peak dynamic unit load versus peak settlement of 30-inch-diameter plate with no overburden.

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FINDINGS AND CONCLUSIONS

1. The NCEL blast simulator and test pit are useful for conducting static and dynamic plate-bearing experiments on soil.

2. The dynamic bearing capacity under the 15-inch-diameter plate was approximately 90 percent greater than the static bearing capacity; i.e., 14.1 versus 7.4 tons per square foot.

3. The k value for the dynamically loaded 15-inch plate was higher than for the statically loaded 15-inch plate; e.g., at a settlement of 0.5 inch, the dynamic k = 226 psi/inch and the static k = 137.7 psi/inch.

4. Though the results of tests on the 30-inch plate are questionable, the indications are that the dynamic k values for the 30-inch plate are less than for the 15-inch plate. This parallels accepted knowledge of statically loaded plate behavior.

5. Again with reservations about the 30-inch test results, the dynamic unit bearing capacity of the 15-inch plate is greater than that of the 30-inch plate. This also parallels accepted knowledge of statically loaded plate behavior.

FUTURE PLANS

The tests reported here were intended, in part, as preparation for more sophisticated experiments, reports of which will be forthcoming. The long-range plan for dynamic bearing capacity research under this task includes investigations of the effects of overburden, type of footing, and soil cohesiveness. The next report in the series will be concerned with a spread footing loaded statically and dynamically on dry sand while under various amounts of overburden. Following that will be studies of a wall or strip footing loaded statically and dynamically on dry sand while under various amounts of overburden. Particular emphasis will be placed upon tests of a strip footing having overburden on one side only, as would be the usual case for the footing of a buried structure.

The effects of soil cohesiveness may be studied experimentally or analytically. If done experimentally, the initial tests probably will be made on sand which has apparent cohesion caused by the introduction of moisture. It is not yet certain whether it will be physically and economically feasible to use a true cohesive soil for bearing capacity experiments in the NCEL blast simulator test pit. Hence analytical techniques may be employed, in conjunction with the results of tests on noncohesive dry sand, to estimate the effects of cohesiveness.

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In future tests in the blast simulator test pit, the width of footing tested will be limited to 12 or 15 inches. This will permit reprocessing the principally affected strata while keeping the depth of necessary reprocessing within reasonable limits.

Improved methods will continue to be sought for placing soil in the test pit so that soil conditions will be uniform throughout. Also, better methods will be sought to measure the true unit weight of the soil in place. For example, a technique of sieving the soil into place is being evaluated for providing uniform density and nonsegregation of grain sizes. Nuclear soil density meters are being considered as a method of measuring density without disturbing the test soil.

ACKNOWLEDGMENTS

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Appendix A

SOIL PROPERTIES

The sand used for plate-bearing tests and certain other soil-structure interaction experiments at NCEL is taken from the bed of the Santa Clara River in Ventura County, California. After being screened and dried by the processor, it is stored in indoor bunkers until placed in the NCEL blast simulator test pit. Since the blast simulator is an indoor facility, the sand has little contact with outdoor atmosphere. Consequently, it remains quite dry throughout the experiments. After several weeks in the test pit, the moisture content of the sand at the end of any test period never reached 0.5 percent through absorption from the atmosphere.

Several separate shipments of sand have been sampled from time to time over a period of several years and found to have remarkably constant grain-size distribution. That distribution is shown in the graph of Figure A-1. The maximum size of the sand is 2.5 mm. The effective size is 0.21 mm, and the uniformity coefficient is 3.

Auxiliary experiments have been made with the NCEL test sand as part of NCEL Task Y-F008-08-03-402 "Fundamental Behavior of Soils Under Time-Dependent Loads." These have included determination of specific gravity, water permeability, one-dimensional consolidation, and angle of internal friction. Some of these values are listed in Table A-1.

Some difficulty was experienced in placing the sand uniformly in the test pit. Every effort was made to spread and compact the sand to a homogeneous grain-size distribution and a uniform density. Random thin strata of size-segregated particles were encountered during density-measurement operations. Improved placement techniques are necessary.

In-place density, or unit weight, of the sand was measured by a method similar to ASTM Designation D-1556-58T, "Density of Soil in Place by the Sand-Cone Method." Since the sand used for the bearing tests was dry, it was impossible to excavate a hole which would retain its size and shape for volume determination with the sand-cone apparatus. It was necessary to modify the density-measuring apparatus to the extent of adding a cylindrical projection to the bottom of the plate used to support the sand cone. A sketch of the apparatus is shown in Figure A-2. In use, the cylinder was inserted into the soil and the cone-support plate was pressed downward until the bottom surface of the plate

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just contacted the soil. Soil then was excavated from within the cylinder. The cavity thus formed was backfilled with sand of known unit weight using the sand-cone method mentioned previously. The calibrated sand used for backfilling was Ottawa Sand, ASTM Designation C-190-59. The unit weight of the test soil in place was calculated using the weight of soil excavated and the weight of calibrated sand used for backfill.

The volume of a cavity as determined by the sand-cone method is reasonably accurate.[11] Also, the weight of soil removed for a density determination can be measured with great accuracy. However, the soil was disturbed by the necessary use of the cylinder to support the cavity wall during excavation and volume measurement. This disturbance was considered great enough, in the tests reported here, to affect the density determination. The average density of the river sand upon which the NCEL plate-bearing tests were made was 109.1 pounds per cubic foot. This value was determined by the modified sand-cone method just described. The maximum and minimum densities of the river sand were found experimentally to be 114.7 and 95.0 pounds per cubic foot.

In another experiment at NCEL which has not yet been reported, sand was placed in the blast simulator test pit in a manner similar to that reported here for the plate-bearing tests. In-place density was measured in the manner reported here. In addition, a log was kept of the weight of river sand placed in the pit. Measurement of the dimensions of that portion of the pit occupied by the sand permitted calculation of the volume and, hence, the density of the sand in place. The sand-cone-cylinder method indicated the density to be 113.1 pounds per cubic foot. The weight log and volume measurement method revealed the density to be 106.9 pounds per cubic foot. Of course, these data are insufficient to provide a correction factor to the plate-bearing-test density data. They do provide evidence of the direction of the error.

Knowledge of the true density of the sand at the times of the bearing test was not as important as uniformity of the density from place to place in the pit and from test to test. As stated in the main body of this report, an attempt to achieve a homogeneous density pattern was made by rigorously adhering to a systematic pattern of placement and vibration. Between tests, a routine of surface loosening and revibration was followed.

For future tests requiring the use of large volumes of soil, better methods of placement and compaction are required. Also needed is a more reliable method of in-place density measurement.
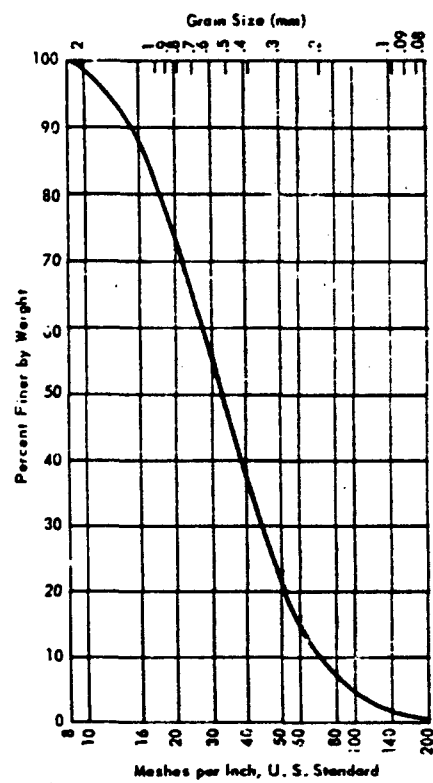
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Figure A-1. Grain-size distribution of sand used for plate-bearing experiments.

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Table A-I. Fundamental Physical Properties of Soil
Used for Plate-Bearing Tests

|	
Type of soil	sand
Secant modulus of compression (consolidometer) at 50 psi:	
at density = 105.8 lb/ft^3	6,500 psi
at density = 111.9 lb/ft^3	10,100 psi
Moisture content	0
Cohesion	0
Angle of internal friction at density $\approx$ 111 lb/ft^3	43°
Specific gravity	2.62
Maximum grain size	2.5 mm
Effective size, D_{10}	0.21 mm
Uniformity coefficient	3
Permeability	
at density = 95 lb/ft^3	0.0116 in./sec
at density = 105 lb/ft^3	0.0096 in./sec
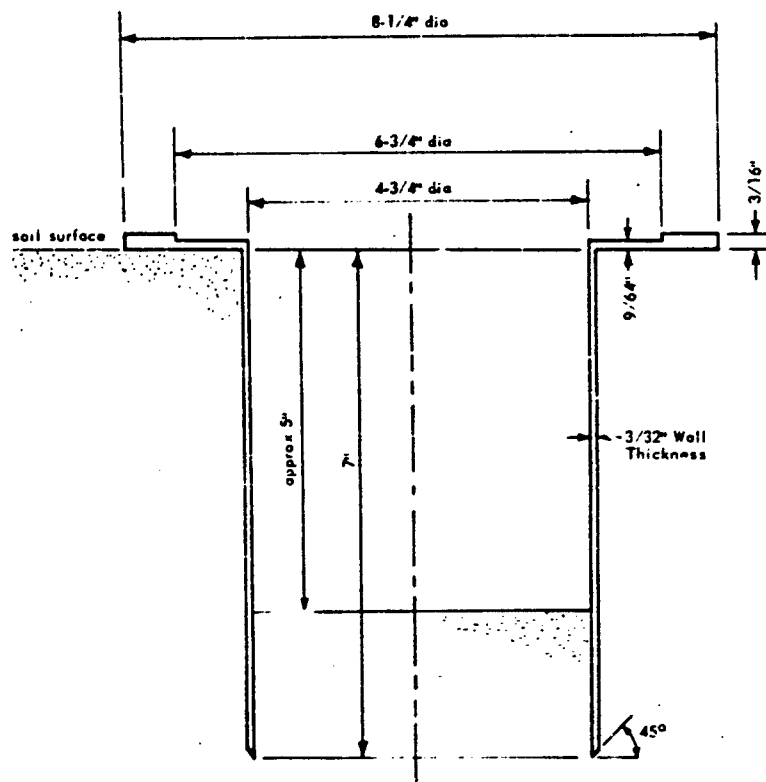
Figure A-2. Cross section of cylindrical wall support device used for sand-cone method of density determination in dry sand.

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Appendix B

INSTRUMENTATION

Only two basic measurements were made during the conduct of the bearing tests — the load on the plate and the settlement of the plate. For the dynamic tests, the load and settlement were recorded against a time base.

Plate settlement during static testing was detected by one of two methods. The first was the conventional use of mechanical strain dials. Four were used, and they were placed to detect vertical motion 1 inch from the edge of the plate on each of four radii 90 degrees apart. The other method of settlement measurement involved replacement of the strain dials by a Bourns Model 108 16-inch-stroke linear-motion potentiometer. It was connected to a four-arm bridge circuit. A schematic of the circuit is shown in Figure B-1. Motion of the plate, and hence of the potentiometer stem, caused an unbalance in the bridge. The unbalance was measured with a Baldwin Type M SR-4 strain indicator. Precalibration of this system against measured motion of the potentiometer stem permitted later computation of the plate settlement. The mechanical strain dials are quite satisfactory for static tests, but the potentiometer was used as a trial for planned future static tests in which strain dials will not be usable. The potentiometer functioned very well for the static tests.

For the dynamic tests, the strain dials naturally could not be used. Instead, the 16-inch potentiometer was used in conjunction with the four-arm bridge. However, automatic recording of the dynamic settlement was necessary, and this was done with a bridge amplifier and recording oscillograph. The electronic amplifying and recording equipment was manufactured by Consolidated Electrodynamics Corporation (CEC). A CEC Type 1-113B carrier amplifier and a CEC Type 7-323 galvanometer were used. This amplifier, with associated power supply, is designated "System D" by the manufacturer. The first tests utilized a CEC Type 5-114 recording oscillograph. Later, this was replaced by a CEC Type 5-119 oscillograph. This equipment is capable of monitoring dynamic phenomena having frequencies up to 600 cycles per second, which is quite adequate for these experiments.

Considerable difficulty was experienced with potentiometer mountings during the dynamic tests. These problems were not attributable to the potentiometer. The flexibility of the mountings and the mass of the moving parts of the potentiometer, though small, produced vibrations in the settlement-measuring system. These vibrations obscured many of the oscillograms of plate settlement

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to the degree that they were unusable. (Toward the end of the series of tests, the trouble was corrected. The potentiometer has worked well on other NCEL experiments not reported here.) A supplementary electromechanical device was used in conjunction with the potentiometer to provide a settlement-time record in the event of failure of the primary potentiometer system. Because of the difficulties mentioned earlier, the supplementary device actually became the primary means of measuring plate settlement. This supplementary device, which may be considered as a rotating-cylinder oscillograph, was developed by personnel of the Structures Division, NCEL. It consists of a spring-loaded pencil, and a paper-covered cylinder which rotates at a constant known speed to provide a time base. In use, the cylinder was so oriented that the spring-loaded pencil, which was attached to the plate-bearing-test loading mechanism, traveled parallel to the axis of the cylinder. The pencil scribed a mark, the excursion of which was equal to the settlement of the bearing plate. Rotation of the cylinder provided the time base from which rates of settlement were computed. This device was not coupled to the load-recording oscillograph, hence the time bases for load and settlement were not synchronized. This precluded analysis of the dynamic test data in terms of load versus settlement at any particular instant of time. However, a study of maximum load versus maximum settlement was possible. Also, it was possible to study load-time and settlement-time phenomena independently.

Static plate loads were measured with a Baldwin Type C SR-4 compression load cell. The load cell was placed between the reaction column and the hydraulic jack used to apply the load. The electronic output of the load cell was read on a Baldwin Type M SR-4 strain indicator. The load cell was previously calibrated with the Type M indicator in a 300-kip compression-testing machine.

Dynamic loads also were measured with a Baldwin Type C SR-4 load cell. For some of the tests, a 100-kip-capacity cell was used. For others, where dictated by anticipated load, a 200-kip cell was used. During dynamic tests, the load cell was operated through CEC "System D" equipment and recorded with the potentiometer-measured settlement data against the same time base in the recording oscillograph. The load cells also were calibrated statically with the "System D" apparatus 300-kip testing machine.
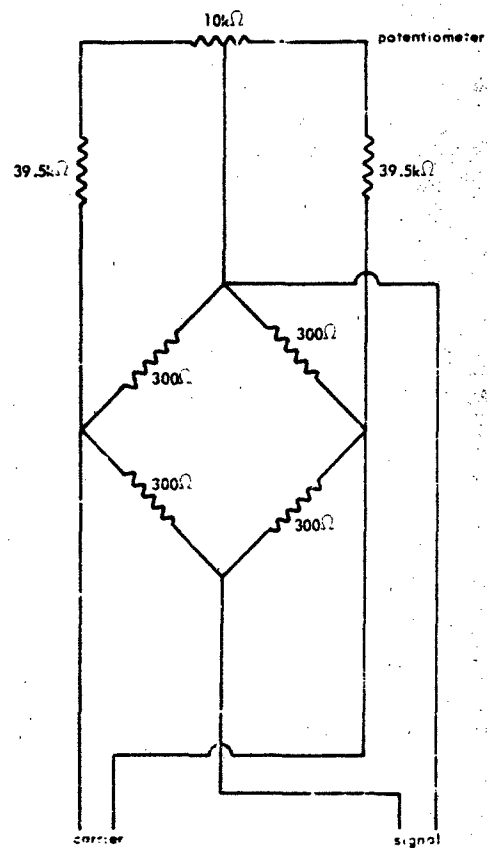
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Figure B-1. Schematic diagram of potentiometer and bridge circuit used to monitor bearing-plate settlement.

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